Virtual Assessment of Structural Health Monitoring Techniques for Wind Turbines Using Vibration Data

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ABSTRACT

Operational Modal Analysis (OMA), also known as output-only modal analysis, allows identifying modal parameters only by using the response measurements of the structure in operational conditions when the input forces cannot be measured. This information can then be used to improve numerical models in order to monitor the operating and structural conditions of the system. This is a critical aspect both for condition monitoring and maintenance of large wind turbines, particularly in the off-shore sector where operation and maintenance represent a high percentage of total costs.

The availability of commercial numerical aeroelastic simulation codes simulating the response of wind turbines in operation can be used as a virtual design and verification tool. Effects of design modifications and variations in the environmental and structural conditions can all be simulated using these tools. However, experimental test campaigns should be able to provide accurate and reliable data with which the model can be updated and be more representative of the real response. Thus, the improvement of these simulation models is strongly related to the improvement of the current Operational Modal Analysis (OMA) modal parameter estimation techniques. The main issue for these methods is that, due to blade rotation, force periodicity and the presence of control surfaces which modify continuously the system configuration, most of the applicability assumptions of OMA are violated. In this paper, some preliminary assessments on how to combine numerical and experimental techniques for Structural Health Monitoring (SHM) of wind turbines are investigated.

INTRODUCTION

Modal parameter estimation, to obtain natural frequencies, modal dampings, mode shapes, is a key step to characterize the dynamical behavior of a structure. Operational Modal Analysis (OMA) is a technique for estimating the modal parameters only on the basis of the measured vibration data without any information on the excitation forces.

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This technique is very attractive for complex structures such as wind turbines that are impossible to excite in an artificial way. The results can then be used for numerical model assessment, for the prediction of dynamic response and for modal parameters evolution and tracking for SHM applications [1].

OMA analyses the response of such structures to natural ambient excitation, i.e. wind, rain, waves, and was successful applied to buildings, stadiums, bridges. Anyway a successful application of OMA requires that the structure and the natural forces exciting it respect certain assumptions; the structure should be linear and time invariant and the excitation forces should be distributed randomly both temporally and spatially [2]. Obviously, the closer is the real excitation to the assumed one, the better the results of the modal parameter estimation will be. Even though the wind excitation can be considered as a perfect excitation obeying to the OMA assumptions, the aeroelastic phenomena, due to the rotor rotation and time-varying nature of wind turbine during operation, set limitations on the applicability of OMA to operational wind turbines.

TIME VARYING NATURE OF OPERATIONAL WIND TURBINES

While application of OMA on parked turbines is straightforward, the same is not true in case of operational turbines, i.e. in power production configuration. This is due to the fact that two of the key OMA assumptions are not respected by an operational wind turbine.

OMA requires the excitation forces to be random broadband and uncorrelated in the frequency range of interest. These assumptions are true when the turbine is in parked conditions, but the blade rotation changes the nature of the aerodynamic forces in a significant way putting several limitations to the application of OMA algorithms. It has been observed that the aerodynamic forces acting on an operational wind turbine are characterized by peaks at rotational frequency and its harmonics; these peaks can mask the modal behavior of the turbine at certain frequencies. This aspect introduces a strong influence of the aerodynamic forces in the observed output responses making the use of OMA for identifying the dynamic characteristics of the structure more complicated than in the parked conditions.

Another important assumption violated by a rotating wind turbine is the time invariance. This assumption states that the structure under test must not change during the test duration, which is not the case for a wind turbine in operational conditions because the different components move with respect to each other. Phenomena like rotation of the rotor about its axis, pitching of the blades and yawing of the nacelle about the tower result in the violation of the OMA assumptions. Several methods can be applied to deal with such variations. First of all a time interval in which the wind turbine is not yawing and the blades are not pitching can be taken into account. In this case the only problem will be the rotation of the rotor about its axis that needs to be analyzed with advanced techniques. From a mathematical point of view, this rotation introduces time-varying terms in the equations of motion of the turbine which results in time-dependent modal parameters that cannot be interpreted as the traditional modal frequencies, damping and mode shapes. One possible solution is to define a methodology that allows analyzing linear time varying systems, but an alternative way to overcome the problem is the application of the so-called Coleman transformation or Multi-Blade Coordinate transformation (MBC).

Coleman transformation

The dynamics of wind turbine rotor blades are expressed in rotating frames attached to the individual blades. Multi-Blade Coordinate transformation allows integrating the dynamics of individual blades expressing it in a fixed nonrotating frame. MBC offers several benefits because it properly models the dynamic interaction between the nonrotating body (tower-nacelle) and the spinning rotor. It also offers physical insight into rotor dynamics and how the rotor interacts with fixed-system entities and it filters out all periodic terms except those which are integral multiples of ΩN, where Ω is the rotor angular speed and N is the number of rotor blades [3].

The main idea behind MBC transformation is to replace individual blade deflections by new variables which include information about the global rotor behavior and about the instantaneous azimuth angle of each blade ψ_b, thus making application of modal analysis techniques, such as OMA, possible.

Consider a rotor with N blades that are spaced equally around the rotor azimuth; in this case the azimuth location of the *b*th blade is given by

$$\psi_b = \psi + (b-1)\frac{2\pi}{N} \qquad (1)$$

where ψ is the azimuth of the first blade considered as the reference blade and $\psi = 0$ means that the first blade is vertically up. If q_b is one of the rotating degree of freedom for the *b*th blade, the MBC relates it to new degrees of freedom defined in a nonrotating fixed frame as:

$$q_0 = \frac{1}{N}\sum_{b=1}^{N} q_b$$

$$q_{nc} = \frac{2}{N}\sum_{b=1}^{N} q_b \cos(n\psi_b) \qquad (2)$$

$$q_{ns} = \frac{2}{N}\sum_{b=1}^{N} q_b \sin(n\psi_b)$$

The physical interpretation of each one of the new coordinates depends on the degree of freedom it refers to. Anyway the new coordinates are able to identify the cumulative behavior of all the blades coupling the rotor with the rest of the turbine.

The transformation is also necessary to better understand different kind of phenomena, such as the rotor shaft whirl behavior that strongly depends on the collective vibratory behavior of the rotor blades.

Whirl modal behavior

The whirl mode behavior has received great attention since it can lead to undesired vibration levels. The analytical formulation, discussed in [4], shows that the whirl-causing shaft forces are generated by two cyclic in-plane modes of the rotor. In a single-frequency whirl mode, the rotating force vector on the shaft is a resultant of two components: a regressive force vector at a lower frequency and a progressive one at higher frequency.

At the blade level, the vibratory motion consists of three components: edgewise motion (in-plane), flapwise motion (out-of-plane) and torsion motion. Flapwise modes are usually dominant in wind turbine and they are well aerodynamically damped. Torsion modes have high frequencies and low amplitudes, so they are not interesting. Finally, dominant edgewise modes must be carefully avoided since they can lead to aeroelastic instabilities.

In this paper, we will focus on the blade edgewise modes since they are associated to the whirl mechanism. First of all modes are calculated in parked conditions where the rotor is not rotating and edgewise modes are well identified. Then the operational conditions in which the rotor is spinning at its nominal speed is considered. It can be seen that the spin increases the frequency due to the centrifugal stiffening. After that, MBC transformation can be applied to transform the blade coordinate into the rotor coordinates to take into account the global rotor behavior and to identify the whirling modes. Nacelle and tower coordinates are not transformed because they are already in a fixed frame of reference.

WIND TURBINE MODEL

Figure 1 show the wind turbine model used in the simulation. The offshore 5MW baseline wind turbine has been developed by the National Renewable Energy Laboratory (NREL) to support concept studies aimed at assessing offshore wind technology. It is a conventional three-bladed upwind variable-speed variable blade-pitch-to-feather-controlled turbine [5]. Since the main objective is to analyze the global dynamic behavior of the full-scale turbine, the model has been built as simple as possible.

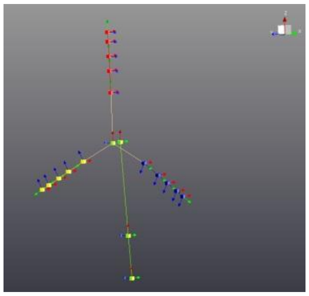

Figure 1: NREL 5 MW SWT model (left) and Test.Lab geometry (right)

- Tower: it is modeled as 5 elastic beam elements with lumped masses and hinged to the ground foundation. The total tower height is 90 m.
- Rotor: in the 3-bladed rotor, each blade is identical and is modeled with 17 sections with specific mass, elastic and aerodynamic properties.
- Drivetrain: the transmission is simplified into a 1 degree-of-freedom system with a gear ratio of 97 between the Low Speed Shaft (LSS) and the High Speed Shaft (HSS).

The wind turbine is modeled and simulated using the nonlinear aeroelastic code SAMCEF Wind Turbines (SWT) that allows the user defining both a structural and an aerodynamic model which are then solved together to obtain the coupled aero-elastic solution [6]. In order to have simulated accelerations that can be considered as those obtained from tri-axial accelerometers mounted on the blades, it is necessary to consider them in the local reference frame in which the X axis is the blade axis (oriented toward the blade tip), the Y axis is aligned with the chord-line and belongs to the blade section plane (oriented toward the leading edge) and the Z axis is normal to the chord line and belongs to the blade section plane. Using this axis configuration, the edge-wise modes are described as bending along the Y axis while flap-wise modes bend the structure along the Z axis. Axial modes along the blade pitch axis can be neglected. Different locations are selected to measure the accelerations; three sensors distributed along the tower, one sensor at the hub center and five sensors per-blade located on the pitch axis [7].

After analyzing the response of the structure in reference and ideal conditions, different possible damages can be introduced to understand how they affect the measured accelerations. In this paper we will focus on the ice formation on the blades. In the software, according to the guidelines for certification of wind turbines, it is possible to introduce the ice on all the blades but one causing a rotor unbalancing situation from which several considerations can be done.

Wind turbine in parked conditions

When the wind turbine is in parked conditions, the first seconds are used to place the pitch in its parking position specified by the parking pitch angle and the rotor at the angle specified by the initial rotor angle. When the true simulation starts, the generator is disconnected (no resisting torque) and the rotor is released while the pitch remains fixed.

In general, long time histories are required for confident modal parameters estimation, but on the other hand a small sampling frequency is necessary to better determine low frequency modes. As a good compromise between these requirements and the computational time, the simulations last 700 seconds and the sampling frequency is set to 100 Hz. Time series are then exported to LMS Test.Lab in which correlations and spectra can be computed and the PolyMAX method can be applied for estimating the modal parameters. Since the interesting modes are at very low frequencies, a down-sampling to 10 Hz has been performed in the first part of the analysis [8].

Table I: Numerical modal parameters in parked conditions for different configurations

	Standard configuration		Ice on all the blades		Ice on all the blades but one	
	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]
1st Tower FA	0.329	5.59	0.324	5.13	0.324	5.24
1st Flap Yaw	0.666	6.20	0.588	7.05	0.585	7.06
1st Edge Yaw	1.059	0.75	0.948	0.95	0.948	0.99
2nd Flap Yaw	1.853	3.24	1.696	2.05	1.695	2.33

Estimated modal frequencies and damping values are shown in Table I which shows the variation of some of these parameters with or without ice on the blades.

Figure 2 shows the power spectral density (PSD) for two different configurations. It shows the shift towards lower frequencies of the two peaks related to the first and second edgewise modes that are taken into account for analyzing the whirl behavior in the following section. The frequency shift is a consequence of the mass increase when the ice is attached to the blades [9].

Wind turbine in operating conditions

When the wind turbine is in operating conditions, the pitch, yaw and generator are managed by the controller to optimize power production and the brake is not used.

While application of OMA on parked turbines is straightforward, the same does not apply to operating turbines. This is due, as mentioned before, to the fact that some of the OMA assumptions are violated by a wind turbine which blades are rotating. In this case accelerations of points on the blades, tower and nacelle are acquired as for the parked conditions. MBC transformation is then applied to the blade accelerations using the azimuth data while the others are left unchanged. Finally, all data are fed to OMA to estimate the modal parameters in operating conditions [10].

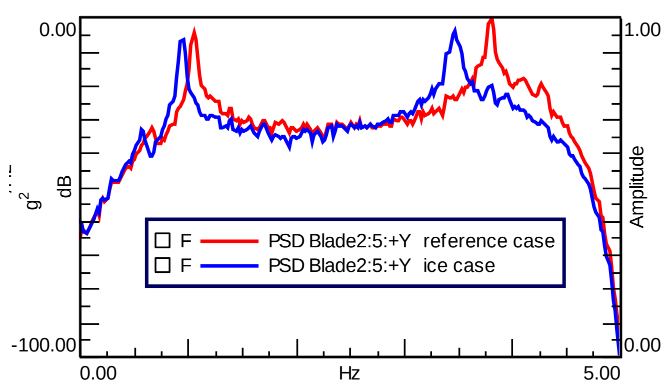

Figure 2: PSDs of accelerations measured on one point on the 2nd blade in edgewise direction in parked conditions. Reference case (red curve) compared to the one with ice on the blade (blue curve)

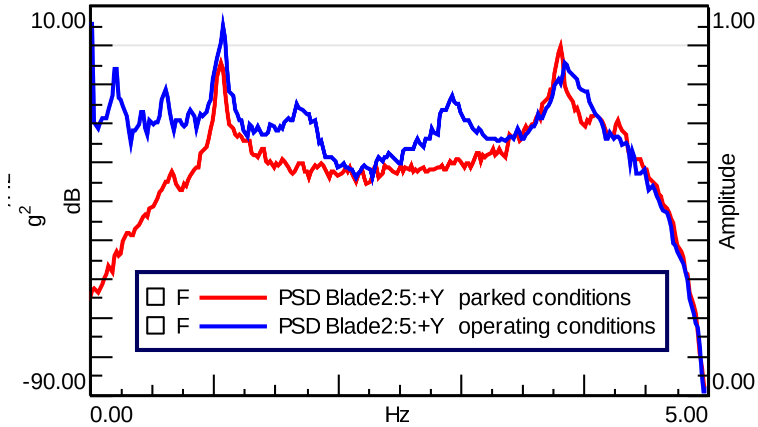

Figure 3: PSDs of accelerations measured at the tip of the blades in parked conditions (red curve) vs. operating conditions (blue curve)

Figure 3 shows a PSDs comparison between parked and operating conditions at the blade tip in the edgewise direction. The frequency shift toward higher frequencies for the first and second edgewise modes due to the centrifugal stiffening can be underlined, while the different harmonic components can be seen in the operating case.

Figure 4 shows the PSDs obtained from the blade accelerations at the tip in the edgewise direction before and after the MBC transformation.

The whirling phenomenon is not observable from experimental data because the blade responses are measured in the rotating coordinate system while whirling can only be observed in a fixed coordinate system [11]. MBC transformation enables observability and identification of whirling modes transforming the blade responses into a ground coordinate system. The two whirling modes are separated by 2ω in accordance with the literature, where ω is the fundamental harmonic frequency equal to 0.217 Hz.

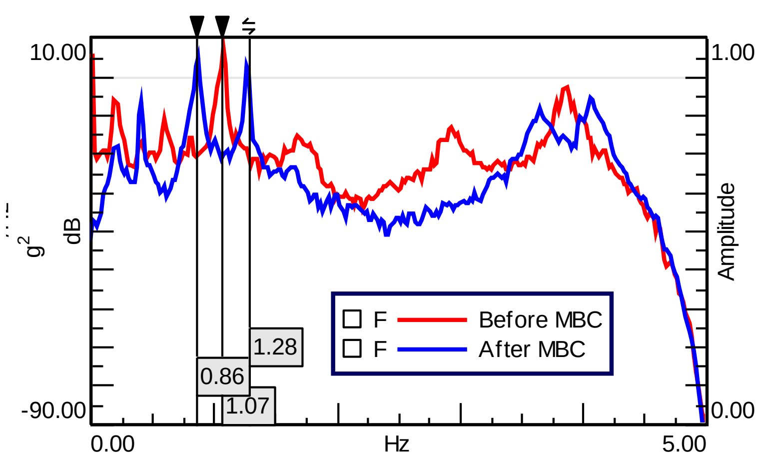

Figure 4: PSDs of accelerations measured at the tip of the blades in operating conditions before (red curve) and after (blue curve) MBC transformation

CONCLUSIONS

The aim of this paper is to understand the applicability of Operational Modal Analysis techniques to operational wind turbines for SHM purposes. The bigger limitation in applying OMA is the presence of harmonics components in the measured spectra. This limitation can be overcome by applying the Coleman transformation to experimental data obtained from blades sensors. The transformation from a rotating reference system to a ground fixed reference system allows identifying the whirl modes that cannot be seen from experimental data and which represent a critical vibration mode. These effects were here investigated and analyzed both in reference as well in damaged configurations (i.e. ice accretions on the blades).

While in this work the accelerations were simulated using an aeroelastic code for wind turbine simulations, the same techniques will soon be applied for structural monitoring of a real wind turbine. The availability of experimental results will also lead to improvement of the associated numerical model, and the two will finally be used together in a combined SHM tool.

REFERENCES

1. B. Peeteers, P. Guillaume, H. Van der Auweraer, B. Cauberghe, P. Verboven, and J. Leuridan, "Automative and aerospace applications of LMS PolyMAX modal parameter estimation method", *Proceedings of IMAC 22, International Modal Analysis Conference*, Dearborn (MI), USA, January 2004.
2. D. Tcherniak, S. Chauhan, M. Rossetti, I. Font, J. Basurko, O. Salgado, "Output-only Modal Analysis on Operating Wind Turbines: Application to Simulated Data", *Proceedings of European Wind Energy Conference*, Warsaw, Poland, April, 2010.
3. G. Bir, "Multiblade Coordinate Transformation and its Application to Wind Turbine Analysis", *Proceedings of 2008 ASME Wind Energy Symposium*, Reno, Nevada, USA, 2008.
4. G. Bir, "Understanding Whirl Modal Behavior of a Wind Turbine Rotor", *Proceedings of IMAC 21, International Modal Analysis Conference*, Orlando (FL), USA, January 2003.
5. J. Jonkman, S. Butterfield, W. Musial, G. Scott, "Definition of a 5-MW Reference Wind Turbine for Offshore System Development", *NREL/TP-500-38060 Technical Report*, USA, February 2009.
6. LMS Samtech Iberica, Samtech Wind Turbines V3.3.02 Online help, Spain, 2012.
7. S. Manzato, D. Moccia, B. Peeters, K. Janssens, J.R. White, "A Review of Harmonic Removal Methods for Improved Operational Modal Analysis of Wind Turbines", *Proceedings of ISMA2012, International Conference on Noise and Vibration Engineering*, Leuven, Belgium, 17-19 September 2012.
8. LMS International, "LMS Test.Lab Rev. 12A", User Manual, Belgium, 2012.
9. E. Di Lorenzo, S. Manzato, B. Peeters, H. Van der Auweraer, "Virtual assessment of damage detection techniques for operational wind turbine", *Proceedings of CMMNO2013, International Conference on Condition Monitoring of Machinery in Non-Stationary Operations,* Ferrara, Italy, 8-10 May 2013.
10. D. Tcherniak, S. Chauhan, M.H. Hansen, "Applicability Limits of Operational Modal Analysis to Operational Wind Turbines", *Proceedings of 28th International Modal Analysis Conference*, Jacksonville (FL), USA, Feb. 2010.
11. M.H. Hansen, "Aeroelastic Instability Problems for Wind Turbines", *Wind Energy* (10), pp. 551-577, 2007.